DOCUMENT RESUME

ED 371 002 TM 021 624

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TITLE Using Construct Validity Techniques To Evaluate an Automated Cognitive Model of Geometric Proof Writing.
PUB DATE Apr 94
NOTE 25p.; Paper presented at the Annual Meeting of the American Educational Research Association (New Orleans, LA, April 4-8, 1994).
PUB TYPE Reports - Research/Technical (143) -- Speeches/Conference Papers (150)

EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS Artificial Intelligence; Cognitive Processes; *Computer Assisted Instruction; Computer Uses in Education; *Construct Validity; Educational Change; *Evaluation Methods; Factor Structure; Geometric Constructions; *Geometry; High Schools; High School Students; *Intelligent Tutoring Systems; Models; Technological Advancement
IDENTIFIERS ANGLE Computer Program; *Automated Cognitive Modeler; Expertise; National Council of Teachers of Mathematics

ABSTRACT

The National Council of Teachers of Mathematics (1991) has identified the use of computers as a necessary teaching tool for enhancing mathematical discourse in schools. One possible vehicle of technological change in mathematics classrooms is the Intelligent Tutoring System (ITS), an artificially intelligent computer-based tutor. This paper reports on 3 construct validity studies that have been conducted with 97 high school students in order to demonstrate the correspondence, or lack thereof, between the theoretical constructs of the Diagram Configuration (DC) Model of geometric proof-writing expertise (Koedinger & Anderson, 1990) and the hints and errors being recorded by an instantiation of the DC Model called ANGLE, an intelligent geometric proof tutor. Results of the studies supported the appropriateness of construct validity techniques for analyzing ITS data. The results partially confirm a hypothesized factor structure for the data. The paper concludes with a discussion of the results, including suggestions for modifications of the ANGLE program. (Contains nine references and six tables.) (Author/SLD)

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USING CONSTRUCT VALIDITY TECHNIQUES TO EVALUATE AN AUTOMATED COGNITIVE MODEL OF GEOMETRIC PROOF WRITING

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ABSTRACT

The National Council of Teachers of Mathematics (1991) has identified the use of computers as a necessary teaching tool for enhancing mathematical discourse in schools. One possible vehicle of technological change in mathematics classrooms is the Intelligent Tutoring System (ITS), an artificially intelligent computer-based tutor. This paper reports on construct validity studies that have been conducted in order to demonstrate the correspondence, or lack thereof, between the theoretical constructs of the Diagram Configuration Model of geometric proof-writing expertise (Koedinger & Anderson, 1990) and the hints and errors being recorded by an instantiation of the DC Model called ANGLE, an intelligent geometric proof tutor. Results of the studies supported the appropriateness of construct validity techniques for analyzing ITS data. The results partially confirmed a hypothesized factor structure for the data. The paper concludes with a discussion of the results, including suggestions for modifications of the ANGLE program.

USING CONSTRUCT VALIDITY TECHNIQUES TO EVALUATE AN AUTOMATED COGNITIVE MODEL OF GEOMETRIC PROOF WRITING

INTRODUCTION

The National Council of Teachers of Mathematics (1991) has identified the use of computers as a necessary teaching tool for enhancing mathematical discourse in schools. Through the use of technology, NCTM (1989) envisions the transformation of classrooms into laboratories for experimentation and exploration, with the consequent altering of the teacher's role to that of a partner in and facilitator of student discovery. One possible vehicle of technological change in mathematics classrooms is the Intelligent Tutoring System (ITS), an artificially intelligent computer-based tutor.

A New Geometry Learning Environment, or ANGLE, is an ITS that was specifically developed as a testbed for a new schema-based cognitive theory of geometric proof-writing called the Diagram Configuration (DC) Model (Koedinger & Anderson, 1990). The system is capable of collecting a large volume of on-line data as students are engaged in problem solving, and this information is used by ANGLE to maintain a model of student cognitions. Collected data includes the number and type of errors committed by a student, the number and type of hints requested by the student, and the time needed to solve a particular problem. Table 1 and Table 2 present a list of error and hint message-types, the abbreviations that will be used in this paper, their meanings, and an example of each.

Insert Tables 1 and 2 About Here

Geometric knowledge in the DC Model is not assumed to be hierarchical, but rather it is theorized to be organized according to diagrammatic schemas. An example of a schema, shown in Figure 1, might be the situation

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Insert Figure 1 About Here

CONGRUENT-TRIANGLES-SHARED-SIDE, in which two congruent triangles share a common side. The DC Model posits that there exist three major processes or constructs in geometric proof-writing:

1. **Diagram Parsing** -- Identifying familiar configurations in the problem diagram and instantiating the corresponding schemas (a body of geometric facts associated with the diagram);
2. **Statement Encoding** -- Comprehending given and goal statements by canonically representing them as part-statements (relationships among parts of the diagram, e.g, AB=DB in Figure 1);
3. **Schema Search** -- Iteratively applying schemas in forward or backward inferences until a link between the given and goal statements is found.

A primary goal of the studies of this paper was to demonstrate the correspondence, or lack thereof, between the theoretical constructs of the DC Model and the hints and errors being recorded by ANGLE.

PURPOSE

As ITS programs become a reality in mathematics classrooms, and as ITS developers become more willing to conduct extensive classroom evaluations of their programs, it will be increasingly important to ensure that there is a viable method of evaluating the validity of the data being gathered by these systems. Further, as data from these models are made available to teachers for use in student assessment, it will be important to avoid the use of redundant or ineffective measures of student performance which might degrade the benefit of computer-assisted evaluations.

The focus of this paper is on the usefulness of construct validation methods for evaluating ITS cognitive models of mathematical performance. The goal of a construct validity study is to maximize the descriptive power of test scores for an individual by maximizing evidential support for the adequacy and appropriateness of the inferences made from those scores (Messick, 1989). Construct validity studies are fundamentally theory-based. That is, for the conclusions of such studies to have any meaning or significance, the traits and measures to be investigated must be supported in theory, and the results of the studies must be interpreted in light of that theory. This paper argues that because ITS automated cognitive models are often instantiations of cognitive learning theories, construct validity studies are appropriate means for enhancing the meaningfulness of ITS on-line data used to generate such models. The questions to be answered by construct validity studies of ITS data include:

-- To what degree is the ITS measuring its target constructs?

-- Is the tutor measuring any unintended constructs?

-- Can some student measures be modified or eliminated from ITS programming due to their ineffectiveness or redundancy in measuring constructs of interest?

METHOD

A laboratory test was conducted at Carnegie-Mellon University during the Summer of 1990, in which student performance with the ANGLE ITS was compared with student use of a first generation Geometry Proof Tutor (GPT) (Koedinger & Anderson, 1993a). Thirty students participated in eight hours of instruction over two weeks, half using ANGLE and half using the GPT. Only the ANGLE portion of the data was used in the first study of this paper.

The purpose of the first study was to determine whether data from ANGLE could be considered sufficiently similar to test scores for an investigation of their construct validity. It was hypothesized that for a subset of similar difficulty problems, the number of error and hint messages received by students would not change appreciably over time as a result of feedback provided by ANGLE. This study involved 15 students solving six medium-difficulty proofs in a laboratory setting (see Table 3 for a listing of problem-types). Two separate repeated measures ANOVA analyses were conducted, one using counts from

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Insert Table 3 About Here

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six error messages and the other employing counts from four hint messages. Each analysis utilized the six problems as six measurement occasions.

A classroom evaluation of ANGLE, involving a total of sixty students, was conducted at a Pittsburgh public high school during April and May, 1992 (Koedinger & Anderson, 1993b). The second study reported here involved 42 students using ANGLE to solve one medium-difficulty proof (Figure 2). The aim of the study was to explore the factor structure of counts from three hint messages and three error messages that were hypothesized specifically to measure the constructs of the DC Model. Exploratory factor analysis, as well as judgmental and logical analyses were used for this purpose.

Insert Figure 2 About Here

The third study analyzed data from the most recent classroom evaluation of ANGLE. Data were collected at a Pittsburgh public high school during April and May, 1993 using a somewhat larger sample than was available for the first classroom assessment. The third study of this paper employed the on-line protocols recorded for 40 students who solved the same problem analyzed in the second study. Confirmatory factor analysis was employed in order more fully to determine the validity of the interpretation of the factors identified in the second study.

RESULTS

First Study

The first study involved a repeated measures ANOVA, using data from each of six problems of similar difficulty-level as six measurement occasions. The analysis employed the ANGLE total message counts for each individual as the dependent variable and occasion (message and problem) as the independent variable. Two separate analyses were conducted, one for error messages and one for hint messages, using Release 4.1 of the statistics package SPSS-X (SPSS, 1988). The variable **PSENTER** was dropped from consideration because of its zero variance for some of the problems. Additionally, one problem for each of three students had to be dropped from consideration because the time to solve the problem was recorded as zero, indicating an ANGLE malfunction for that problem.

For the main effect of occasion, there were no significant multivariate or univariate results for the dependent measures of either analysis ($p>.05$). The two analyses produced five combinations of occasions for each error or hint variable. For a conservative test, the five combinations for each variable were considered as one scale with a p-level of $.05/5=.01$ for each combination. Out of 30 possible combinations of occasions for six error messages, only **WPJUSTER** had significant F value ($p=.009$) for the combination involving problems 1, 2, 3 and 6.

None of 20 possible combinations of occasions for four hint messages were significant at the .01 level.

Overall, the repeated measures analyses indicated the general consistency of both error and hint messages across a subset of six similar difficulty level problems. These results provided evidence to support the assumption that, for a subset of six problems of similar difficulty, error and hint messages did not change appreciably for individuals as a result of tutor feedback. That is, ANGLE on-line measures could be considered sufficiently similar to test scores for an investigation of their construct validity.

Second Study

For the classroom evaluation, the execution phase of proof construction was turned off by its developers, eliminating the recording of the on-line variables **EXJUSTER** and **EXJUSTHT**. The second study began with a principal components analysis and an exploratory factor analysis. Both analyses were run using Release 4.0 of the statistics package SPSS-X (SPSS, 1988). The Kaiser-Meyer-Olkin measure of sampling adequacy for the dataset was .66571, which is satisfactory (Tabachnick & Fidell, 1989).

Since **PSENTER** was only experienced once by one student, and **MSJUSTER** and **MSIOER** could not be considered to measure one of the hypothesized constructs, only six variables were included in the principal components and factor analyses. One error and one hint message were hypothesized by this author to measure each of the three theoretical constructs of the DC Model (Figure 3). The constructs are depicted as ovals and the ANGLE measures as rectangles. The curved arrows represent simple correlations

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Insert Figure 3 About Here

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between constructs and the longer straight arrows indicate the hypothesized causal relationships between constructs and measures. The smaller arrows at the bottom of the figure portray residual variances from unspecified influences (e.g., measurement error).

The principal components analysis calculated a correlation matrix for the six messages, as well as eigenvalues and explained variance statistics, which are shown in Table 4. Note that for a principal components analysis, values of 1 are placed in the diagonal of the correlation matrix; these values are replaced with squared multiple correlations for factor analysis. The principal components

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Insert Table 4 About Here

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analysis extracted two factors, each with an eigenvalue greater than 1.00, which were capable of explaining 63 percent of the variance for the six categories of messages. Therefore, a two factor model was explored using both a VARIMAX (orthogonal) and OBLIMIN (oblique) rotation. For the OBLIMIN solution, the two factors were found to have a correlation of .47823, or a substantial 23% overlap in variance (Table 5). Additionally, all loadings for the VARIMAX rotation were positive, a further indication that an OBLIMIN solution was appropriate for the data.

Insert Table 5 About Here

All three error messages and one hint message (SCJUSTHT) loaded on Factor 1, while the two remaining hint messages loaded on Factor 2. The Cronbach-alpha value for Factor 1 was .78, which was considered reasonable; the same consistency measure was only .38 for Factor 2, denoting a lack of stability for the measures of the factor. The error and hint messages hypothesized to measure the construct of Schema Search both loaded on Factor 1, indicating a possible identity for the factor.

In an effort to further identify the factors produced in each of the above analyses, judgmental and logical evaluations were made of the ANGLE data, illuminated by the literature on ANGLE. With regard to **CFENTER** and **PSJUSTER** loading on Factor 1, Koedinger and Anderson (1993b) have made the point that "... a few students occasionally took a rather mindless trial-and-error approach to working with ANGLE." (p. 247). This approach involved students using feedback received from ANGLE in order to guide them in their proof-writing. The developers' observation was supported by the loading of the error messages **WPJUSTER, CFENTER** and **PSJUSTER** on a single factor.

Nevertheless, the identity of Factor 1 as primarily Schema Search is still reasonable given the strong loadings of **WPJUSTER** and **SCJUSTHT**. Whereas it might have been relatively easy (though time-consuming) for novices to instantiate schemas and choose part-statements by intentionally making errors, it proved to be much more difficult to establish ways-to-prove in the same manner; hence the loading of **SCJUSTHT** with **WPJUSTER** on Factor 1. It appears that the Schema Search aspect of proof writing presented more challenges for the novices of the classroom study than other proficiencies.

Given the fact that the Cronbach-alpha coefficient was low for the measures **SCSELHT** and **PSJUSTHT**, any rival hypothesis concerning Factor 2 would be considered tenuous at best. There is certainly a relationship between the two hint options, and that relationship might be interpreted as method-specific variance produced by a dependence of some students on **SCSELHT** and **PSJUSTHT** to help them get through the schema selection and part-statement justification portions of the proof without making errors. Overall, though, the validity of the interpretation that the two hint variables measured either of the constructs Diagram Parsing or Statement Encoding was not supported in the results.

__Third Study__

A confirmatory factor analysis was run using Version 3.0a of the EQS Structural Equation Program (Bentler, 1989). The analysis used the factor structure specified in Table 5 in an attempt to confirm the measurement model's goodness-of-fit for a different sample of students. Table 6 contains the results of the confirmatory analysis, including goodness-of-fit indices, factor loadings and standardized residuals.

The Bentler-Bonett Normed Fit Index value of .974 exceeded the minimum recommended value of .90 (Tabachnick & Fidell, 1989), an indication of the appropriateness of the measurement model. The Chi-Square test and the Bentler-Bonett Nonnormed Fit Index agreed with this result. The factor loading and standardized residuals results reveal that PSJUSTER is the primary cause of a lack of fit of the model to the data. Note that relative loadings of the variables in the confirmatory analysis agree with those of the exploratory analysis, though the actual values were lower for the Factor 1 measures. It should be pointed out that the variance for each of the variables of the dataset was low; therefore, minor differences in student response patterns from those of the dataset could have a significant impact on the fit indices reported for this analysis.

DISCUSSION

A primary goal of any construct validity study is to provide information concerning the strength of measures of traits or abilities, so that those measures may be reformulated or refined to measure more accurately the constructs of interest. The results of the second and third studies suggested that the unanticipated loading of all error messages provided by ANGLE on a single

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factor was reflective of the fact that students were using those messages to guide their proof-writing. It is certainly possible that some of the students consciously used the error messages as a means of learning how to write correct proofs, but given the developers' observations of students at work with ANGLE (Koedinger & Anderson, 1993b), it seems unlikely that use of error feedback was anything more than a "work-around" in order to get through the proof.

Given the above, it is useful to speculate on changes that might be made in the design of ANGLE in order to force students to take a less random approach to proof-writing. Since "guess-and-check" is a legitimate problem-solving strategy presently being taught in school mathematics, it would probably not be a good idea to simply penalize guessing by, say, shutting off the feedback option at some point in a proof. Therefore, it might be advisable to establish a beginning point total or score for a given proof. Each error committed or, possibly, each hint requested (though this is really a separate issue) would deduct from the total score for the problem. Thus, students would have two goals for any proof: write the proof correctly, and maintain the point total in some acceptable range. Writing proofs then becomes a game to be won and thus hopefully more motivating and involving for students.

Another issue arising from the second and third studies was the lack of evidence for an interpretation of any variables actually measuring the constructs Diagram Parsing and Statement Encoding. It may be that the loadings of the error measures would change if the use of error feedback was more regulated, as suggested above. It may also be that the measures are simply too global to effectively measure the traits of interest. That is, a category of error messages such as **PSJUSTER** might need to be subdivided into narrower categories of messages that reflect more clearly the different stages of proof construction; this would be especially important for more complicated proofs involving many

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steps. Further, the viability of subdividing different categories of error and hint messages might then suggest the possibility of the existence of more constructs. This possibility could be investigated via additional exploratory analyses, such as those of the second study.

As ITS programs become a reality in mathematics classrooms, and as ITS developers become more willing to conduct extensive classroom evaluations of their programs, it will be increasingly important to ensure that there is a viable method of evaluating the validity of the data being gathered by these systems. Further, as data from these models are made available to teachers for use in student assessment, studies such as those of this paper will also be helpful in avoiding the use of redundant or ineffective measures of student performance which might degrade the benefit of computer-assisted evaluations.

It should be understood that the evaluation methods being suggested in this paper are intended to be iterative in nature, and thus it is unrealistic for an ITS developer or evaluator to believe that one or two evaluation cycles would be sufficient to determine fully the construct validity of inferences drawn from recorded variables. Nonetheless, if the ultimate goal is to develop an artificially-intelligent system which is capable of meaningfully interpreting the cognitive processes of its users, construct validity studies represent an accessible, theory-based approach to evaluating automated cognitive models.

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AUTHOR NOTES

The author gratefully acknowledges the assistance provided by Kenneth R. Koedinger of Carnegie-Mellon University, who supplied the ANGLE datasets analyzed in the studies of this paper, as well as many useful insights concerning the ANGLE program and the students that used it.

Table 1. ANGLE Error Messages

Configuration Entry Error (CFENTER) - Failing to correctly identify/enter a diagram configuration

Example: "This concept [e.g., CONGRUENT-TRIANGLES-SHARED-SIDE] does not appear in the diagram."

Part-Statement Entry Error (PSENTER) - Failing to correctly enter a part-statement

Example: "If the diagram is drawn accurately, angles which don't look equal cannot be proven equal."

Part-Statement Justification Error (PSJUSTER) - Failing to correctly justify a part-statement

Example: "To justify a statement, like DB=HF, you need to use a concept in which DB=HF is a part-statement."

Ways-to-Prove Justification Error (WPJUSTER) - Failing to correctly justify a schema

Example: "The statements you selected are part-statements of ΔABF=ΔCBG, but they do not match any of the ways-to-prove."

Execution Justification Error (EXJUSTER) - Failing to correctly justify or insert a rule

Example: "The REFLEXIVE rule does not need any premises. It is justified by the diagram."

Miscellaneous Justification Error (MSJUSTER) - Other justification errors

Example: "You are trying to use ΔPQW=ΔPSW to prove itself. That line of reasoning is circular."

Miscellaneous Input/Output Error (MSIOER) - Other interface errors

Example: "To finish selecting premises, click on DONE or ABORT."

Table 2. ANGLE Hint Messages

Schema Selection Hint (SCSELHT) - Hints for entering a schema

Example: "Try to find two triangles which look congruent."

Part-statement Justification Hint (PSJUSTHT) - Hints for entering and justifying part-statements

Example: "Look for OVERLAPPING concepts. That is, look for a part-statement which appears in both ΔABF=ΔCBG and in a concept you've already proven."

Schema Justification Hint (SCJUSTHT) - Hints for justifying a schema

Example: "Find proven part-statements of ΔABD=ΔEFH and use them to justify it."

Execution Justification Hint (EXJUSTHT) - Hints for adding rules

Example: "Prove RQ=RS using the CORRES-PARTS rule."

Figure 1. Diagram of ANGLE's CONGRUENT-TRIANGLES-SHARED-SIDE Schema

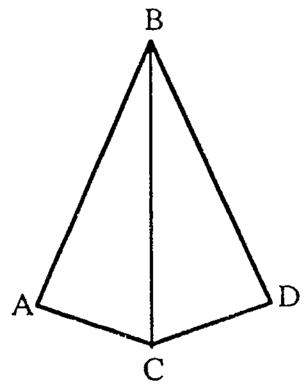

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Table 3. ANGLE Problems Analyzed During the First Study

Problem 1 - Prove triangles congruent using Angle-Angle-Side (AAS);

Problem 2 - Prove triangles congruent using AAS and then prove angles congruent using Corresponding Parts of Congruent Triangles are Congruent (CPCTC);

Problem 3 - Prove triangles congruent using AAS;

Problem 4 - Prove triangles congruent using AAS;

Problem 5 - Prove triangles congruent using Side-Angle-Side (SAS);

Problem 6 - Prove triangles congruent using SAS and then prove angles congruent using CPCTC.

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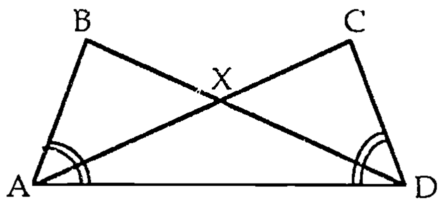
Figure 2. ANGLE Problem Analyzed for the Second Study



GIVENS: <ADX=<XAD
<ADC=<BAD

GOAL: AB=DC

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Figure 3. Hypothesized Path Diagram Model for ANGLE

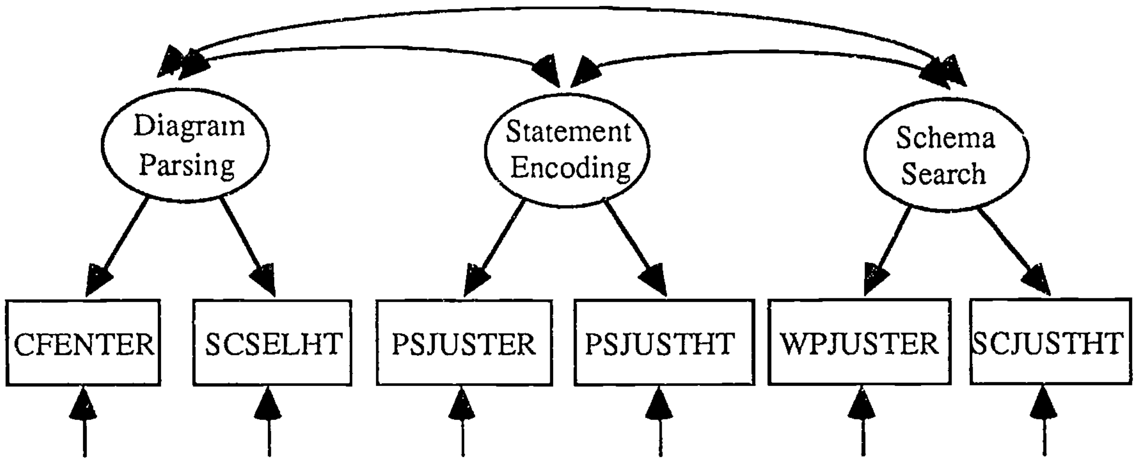

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Table 4. **Principal Components Analysis Results for ANGLE**

	Items (messages)					
	CFENTER	PSJUSTER	WPJUSTER	SCSELHT	PSJUSTHT	SCJUSTHT
CFENTER	1.00000					
PSJUSTER	.31727	1.00000				
WPJUSTER	.38579	.35378	1.00000			
SCSELHT	.17924	.21021	.15904	1.00000		
PSJUSTHT	.27761	.07580	.37233	.34715	1.00000	
SCJUSTHT	.44394	.39829	.84451	.22094	.30404	1.00000

Factor	Eigenvalue	Percent of Variance	Cumulative Percent
1	2.72597	45.4	45.4
2	1.05621	17.6	63.0

Table 5. Rotated Factor Matrices for ANGLE

Pattern Matrix:

MESSAGE-TYPE	FACTOR 1	FACTOR 2
SCJUSTHT	.99010	-.09946
WPJUSTER	.92111	-.09057
CFENTER	.41881	.15942
PSJUSTER	.38966	.08262
SCSELHT	-.06103	.68919
PSJUSTHT	.17636	.43905

Structure Matrix:

MESSAGE-TYPE	FACTOR 1	FACTOR 2
SCJUSTHT	.94254	.37404
WPJUSTER	.87780	.34993
CFENTER	.49505	.35971
PSJUSTER	.42917	.26897
SCSELHT	.26855	.66000
PSJUSTHT	.38633	.52339

Table 6. Results of the ANGLE Confirmatory Factor Analysis

Factor Loadings with Standardized Residuals:

VARIABLE	FACTOR1	FACTOR2	RESIDUALS
SCJUSTHT	.580	--	.815
WPJUSTER	.468	--	.884
CFENTER	.363	--	.932
PSJUSTER	.205	--	.979
SCSELHT	--	1.000	.000
PSJUSTHT	--	.970	.244

Goodness-of-fit Indices:

Chi-Square = 3.066 with 8 d.f. Non-Significant (p=.93012)
Bentler-Bonett Normed Fit Index = 0.974
Bentler-Bonett Nonnormed Fit Index = 1.088